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DESIGN, CONSTRUCTION, AND PERFORMANCE OF CRYOGENICALLY
COOLED AND SUPERCONDUCTING ELECTROMAGNETS

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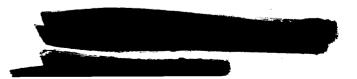
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29352

Cryogenically Cooled Coils

Cryogenically cooled and superconducting electromagnets of large volume for research in plasma physics, solid state physics, and MHD power generation have been designed, constructed, and tested at the NASA Lewis Research Center.

One system of coils, wound from ultrapure (99.9983 percent pure) aluminum and cooled with liquid neon, has produced steady-state fields as large as 200 kG in a 11.2 cm bore and 80 kG in a 30 cm bore. Both magnets are in current use, providing intense fields of large volume for physics research. Superconducting coils have been wound from niobium-zirconium and niobium-tin wires and ribbons. These have produced fields as intense as 50 kG with niobium-zirconium coils and 80 kG with niobium-tin coils in a 10 cm bore.

The performance of these coils, by themselves and in combination, to produce magnetic bottles with superimposed cusp fields will be described.

INTRODUCTION

The research being conducted at the NASA Lewis Research Center requires magnetic fields of large volume and high field strength. To satisfy these needs a program of design, development, and testing of magnets has been under way for several years. This research and development has been concerned with three types of electromagnets: (1) copper coils cooled with water, (2) aluminum coils cryogenically cooled, and (3) superconducting coils.

These electromagnets have been and are being used for investigations in plasma and solid-state physics, in magnetohydrodynamic (MHD) power generation, in the effect of magnetic fields on animal life, and in other fields. The magnetic facilities that have resulted from this program will be described in this article.

Water-Cooled Copper Coils

The copper water-cooled electromagnets are somewhat uniquely designed to take advantage of the homopolar generator that supplies their power. The two magnets have bores of 5 and 10 cm, respectively, and produce fields of 110 and 88.5 kG, respectively. Their unique features are very low impedance, radial flow of coolant, coolant water taken from mains and discharged to the sewer (no special treatment required), and no ripple in the field. These magnets have been used extensively in research, especially in the high field properties of superconductors.

The cryogenically cooled aluminum electromagnets2 were designed at Lewis Research Center and were produced under contracts for the component parts. Assembly and testing were done at Lewis.

High purity aluminum was selected as the conductor because of the magnetoresistance characteristics of aluminum. The resistance of aluminum changes in a magnetic field, increasing at low fields and saturating at high fields. This saturation in magnetoresistance is a function of both the temperature and the purity of the conductor. The highest purity available in large quantities at a reasonable price was 0.999983 and this was the conductor selected for the coils. Extensive measurements of the magnetoresistance of 0.99999+ and 0.999983 pure aluminum were made at the National Bureau of Standards and at the Lewis Research Center. These results are shown in Fig. 1. Similar measurements of the magnetoresistance of copper did not show this saturation. Hence, aluminum was the choice.

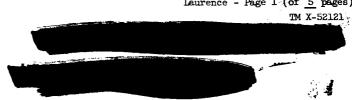
The selection of a coolant was likewise dictated by practical considerations. Liquid helium was not used because of its low latent heat of vaporization. Liquid hydrogen was not considered because of the explosion hazard - especially dangerous at our location adjacent to Cleveland Hopkins International Airport. Liquid neon was chosen as the best available coolant becaust it is inert and it is available in reasonable quantities as a byproduct of the steel industry's liquid oxygen plants.

The liquid neon plant used in this installation was described3 at the 1964 Cryogenic Engineering Conference at Philadelphia and will not be described here except to say that it is a completely closed system. All the neon, boiled off in cooling the magnets, is recovered and reliquefied for re-

Construction Details

Because the high-purity annealed aluminum is so soft, special methods had to be developed for handling the material and restraining the magnetic forces in the conductor. These details are shown in Fig. 2. A backup channel of stainless steel contains the high purity aluminum which is bonded to it by a thermosetting adhesive. The flow channels for the coolant are formed by stainless steel spacers which are held in position by means of a thin (0.003 in.), stainless, corrugated carrier

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ribbon. Between turns, insulation is provided by a fiberglass scrim cloth. The complete package is wound up to form a flat pancake with the dimensions shown in Table I. A photograph of a pair of completed coils is shown in Fig. 3. In this photograph the method of attachment of the bus bars to the coils can be seen. In all cases, the coils are connected in series in pairs and pairs of coils are sometimes in parallel and other times in series.

A photograph of the complete set of coils installed in the cryostat is shown in Fig. 4. This photograph was taken after the maximum power run in which a field of 200±1 kG was obtained. In the photograph, the bus leads can be seen as well as the liquid level gages and instrumentation leads to the coils.

The completed magnet facility is shown in Fig. 5. Fig. 5(a) shows the bottom of the cryostat while Fig. 5(b) shows the top. In the first of these photographs, the liquid neon transfer line can be seen as well as the vacuum pumps which exhaust the vacuum jackets on the cryostat. In the picture of the top of the cryostat, the vaporreturn pipe, the television camera port, the illumination port, and the research Dewar can be seen. This research Dewar can provide either room temperature or liquid helium temperatures, whichever is required by the experimenter.

A schematic drawing of the entire cryostat, including magnet coils, bus bars, television, and lighting ports, is shown in Fig. 6.

Operation of the magnets. - The aluminum coils of the cryomagnets have been extensively tested in pairs and in combination of pairs, as shown in Table I. The six 29.2-cm bore coils were run in series while the eight 11.2 cm bore coils were run in two pairs of four each in electrical parallel connection. The results of a series of test runs of the 8-coil configuration are given in Table II and Fig. 7.

During operation of the magnet, the pressure in the vapor tank increases rapidly with a corresponding increase in the boiling temperature of the liquid neon. This effect is illustrated by the scatter in the data of Fig. 7 and also by the curves of Fig. 8 where the coil resistance is plotted as a function of current with neon vapor pressure as a parameter. Hence, in operating the magnet, the resistance does not stay constant. A load line, therefore, cuts across this family of curves and the power required to produce a given field increases faster than the square of the current.

The limited amount of cooling available (1 mW, minimum 6×10^7 J) in the form of liquid neon is, of course, the most serious disadvantage of the cryomagnets. It limits the amount of time available for an experiment and, since 20 hours are required to reliquefy the neon, only one run per day can be scheduled. Hence, the experiments to be run in this facility must be well planned and programed to work around this limitation.

Auxiliary Equipment and Instrumentation

The power to operate the cryomagnets is provided by a homopolar generator which is limited in output voltage to 38 volts, but which will supply more than sufficient current.

The level of the liquid neon is monitored by capacitance-type liquid-level gages, which provide a continuous indication of the neon level. During actual operation, the indications of the gages are somewhat affected by the vigorous boiling of the liquid. Monitoring of the inside of the tank by means of closed-circuit television is provided.

The field measurements are provided by rotating coil, Hall devices, magnetoresistance probes, and other standard field measurement devices. The calculated G/A ratio agrees very closely with the measured values and can ordinarily be used as an accurate method of determining the field (see Fig. 7).

The coil currents, potential difference across the individual coils, temperature sensors, pressure above the liquid in the tank, and other parameters are recorded on strip chart recorders. The data signals are likewise automatically recorded to make possible the conduction of an experiment in the limited running time available.

Superconducting Magnets

Superconducting magnets have also been under investigation at Lewis Research Center. Coils of various sizes have been wound in-house and on contract with coil manufacturers. In addition, Lewis has had several contracts with the Radio Corporation of America to produce large-size and high field-strength magnets.⁴

In this article, a superconducting magnetic bottle for plasma physics experiments will be described. This magnetic bottle (Fig. 9) provides two mirror coils A and C and a center field coil B to give a relatively long center field of constant value and 2:1 mirror ratio. An integral part of this bottle is a superimposed quadrupole field equivalent to 5 to 10 percent of the center field. This provides a cusp field in the manner proposed by Ioffe, et al., 5 and the conductors are called Ioffe bars.

Design and construction. - The fields to be provided by this magnetic bottle were 50 kG for the mirror coils, 25 kG for the field coil and 1 to 2 kG for the Loffe bars. In order to provide fields of this kind, a niobium - 25-percent zirconium superconducting cable, consisting of seven strands of copper-plated niobium-zirconium wire bundled together and potted with 0.99999 indium metal and insulated with either Teflon or Mylar, was chosen as the conductor. The design parameters of these coils are shown in Table I and in Fig. 10.

The coils were designed to use the minimum wire length to produce the given fields and spacing

was provided between the coils for radial access to the axis of the coils, as required by the plasma physicists.

To accomplish this design, coil forms were made up of stainless steel and the coils were wound with the results shown in the photographs of Figs. ll and 12. Fig. ll shows the scheme used to wind the quadrupole configuration. A split piece of stainless tubing was welded to a larger tube to provide channels in which to wind the superconducting wire. Fig. ll(a) is a photograph of a completed coil with the superconducting cable, before potting with an epoxy resin. Fig. ll(b) is a schematic of the current path along the conductors forming the Ioffe bar.

Fig. 12 shows the completed magnet assembly consisting of the two mirror coils, the field coil, and the Ioffe coil (hidden from view) which is inside these three. The mirror coils were potted and were restrained on the outside by a layer of nylon cord. The coils were wound with an interlayer of aluminum foil and an interlayer insulation of Mylar tape. They were driven normal many times with little or no damage to the coils.

Because of variations in the size of the superconducting cable (different insulations result in different overall diameters), the actual number of turns and layers differed somewhat from the design, and are shown in Table IV. These changes in the length of wire, number of turns, and number of layers give somewhat larger fields for design current or the same fields as the design coils for less current.

The leads to the superconducting coils were of some concern for two reasons: (1) because of the number of them that would be required if it were necessary to power the coils individually, and (2) because of their size that would be necessarily large, to carry the design current (175 A) into the liquid helium environment. Both of these factors increase the heat leak into the Dewar with consequent high helium loss.

The superconducting-to-normal contacts were made by soldering the copper indium-coated superconductor to a channel of high purity copper with indium-tin solder. The channel was then bolted to the coil forms with nylon bolts for insulation. The contacts usually resulted in a resistence of 0.1 to 0.2 microohms between the copper and the superconductor. This resistance was low enough for successful operation of the coils.

Results and Discussion

The results obtained by operating the coils both alone and in combination are shown in Figs. 13 to 18. These figures show the charging history of the coils, with the current plotted on the y-axis and the charging time plotted on the x-axis. The charging rate of the coils was varied over large ranges and was of no consequence except when three or four of the coils were connected in series.

Fig. 13 shows the result of charging the top coil (M₁) alone. All the coils in the magnetic bottle are shunted by silicon diodes in all the tests for protection against voltage buildup when only one or two of the coils are driven normal. Fig. 13 shows that coil A carried a maximum of 173 A and produced a field of 52.0 kG when it went normal.

Figs. 14, 15, and 16 show similar results for the bottom coil C, the center coil B, and the Ioffe bars, respectively, as they were charged and driven normal. The critical-current and criticalfield values are shown on the figures.

Tests of all four coils in series (Fig. 17) were disappointing in that the coils were driven normal when the current exceeded 85 to 95 A. Since this is only about half the design current, this method of operation was quite unsatisfactory and the results mean that more than one power supply is required for successful operation. Using one power supply on the three coils in series at 148 A, the Ioffe bar current from a second power supply was 88 A at the time the Ioffe bar went normal.

Fig. 18 shows the result of operating coils M_1 , M_2 , and M_3 in series. For a slow-charging ratio, these coils can be operated at a current level of 152 A and a field of 47 kG (sufficient to give the desired mirror ratio as well as the desired central fields). It is entirely possible that a separate power supply for the Ioffe bar, and additional turns of cable on it to provide for lower operating currents, may be a better solution than the present coils.

Conclusion

The magnetic-field requirements of research workers at the NASA Lewis Research are being met by conventional (water-cooled), cryogenically cooled and superconducting magnets of high field strength and large volume. These magnets have been designed, constructed, and tested to show the feasibility of the concept and are being used for plasma physics, solid state physics, and MHD-powergeneration research.

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TABLE I. - SPECIFICATIONS OF CRYOGENICALLY

TABLE II. - OPERATION OF 11.2-CENTIMETER
BORE CRYOMAGNET

COOLED ALUMINUM MAGNETS

Specification	11.2-cm bore	29.2-cm bore
Number of coils Ratio of number of turns to coil	8 ~ 90	6 ~ 75
Packing fraction Electrical dimensions, cm	0.4	0.4
Inner diameter	13.0	30.5
Outer diameter	94	94
Ratio of outer to inner diameter	7.1	3.1
Ratio of length to inner diameter	4.0	1.3
Space inside liquid-helium Dewar, cm	6.4	23
Space inside magnet core at room temperature	6.4	23
Maximum field accomplished	199.0	80
Maximum current, kA	30.4	10.0
Voltage total, V	34.3	22.9
Power consumed, mW	1.042	0.229
Gauss-Ampere ratio	13.1	8.0
Stored energy, mJ	9.4	3.6

Date	Current, kA	Magnetic field,	Potential difference across coil, V	Power, kW
4-30	7.0	92	11.6	162
5-3	9.9	130	18.8	372
5-3	7.9	104	12.7	201
5-4	10.5	138	18.0	378
5-5	12.4	162	22.0	545
5-6	12.9	169	24.5	634
5-7	13.7	180	27.0	742
5-10	14.3	188	30.0	858
5-11	10.7	140	20.6	441
5-12	14.8	194	31.0	918
5-14	15.2	199	33.0	1004

TABLE III. - COIL DIMENSIONS

Coil Magnetic field at center of coil	Coil dimensions		Ratio of	Ratio of	Length	Number	Number	
	Length of coil, in.	Inner diameter, in.		length to inner diameter	of wire, ft	of turns	of layers	
A C	48.5 kG 48.5	5 5	4	2.0	1.2	7500 7500	4550 4550	44 44
В	16.0	4 3 16	4	1.3	1.0	1440	1131	13
Ioffe bars	5 to 10 percent	20	$2\frac{7}{8}$			415	60	

TABLE IV. - ACTUAL COIL DIMENSIONS

Coil	Number of turns		
A	4800	43	8000
C	4785	43	8000
B	1152	14	1440
Ioffe bars	60		415

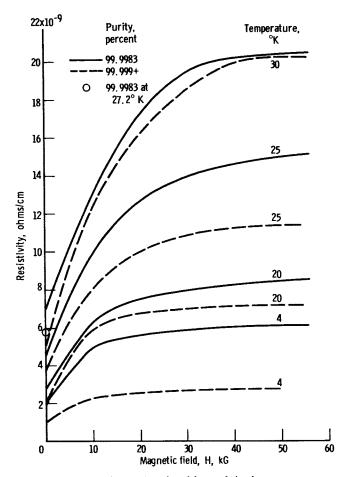


Fig. 1. Magnetoresistance of aluminum.

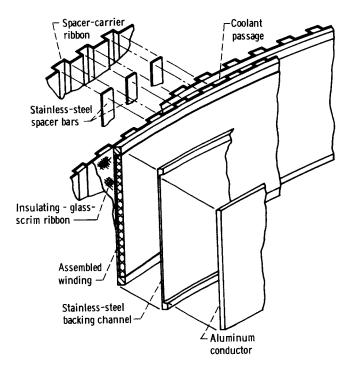


Fig. 2. - Construction of coils of cryogenically-cooled aluminum magnet.

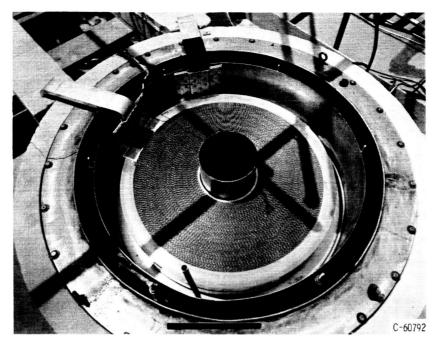
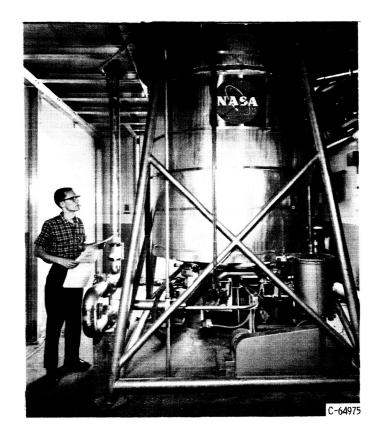


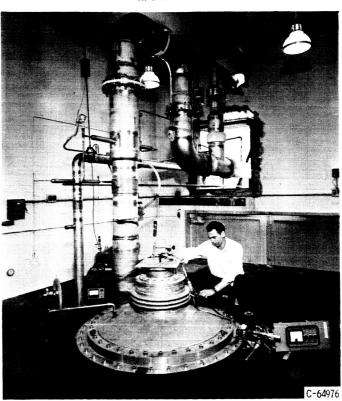
Fig. 3. - Coils in dewar.



Fig. 4. - Magnet coils installed in cryostat.



(a) Bottom view.



(b) Top view.

Fig. 5. - Neon-cooled electromagnet containment vessel.

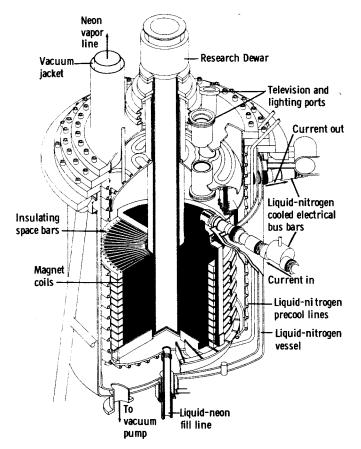


Fig. 6. - Liquid-neon-cooled aluminum electromagnet.

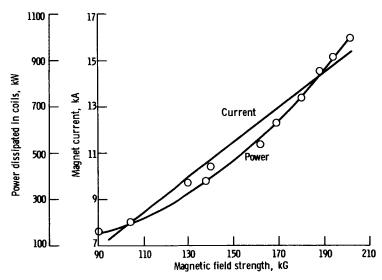


Fig. 7. Operation of 11.2 cm bore cryomagnet; G/A = 13.1.

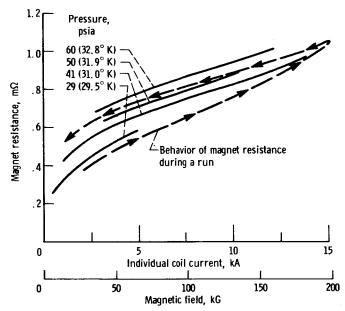


Fig. 8. Resistance of eight $4\frac{1}{2}$ -in. -bore coils (in series-parallel hookup) as function of individual coil current.

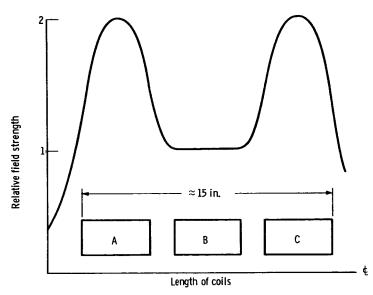


Fig. 9. Magnetic mirror configuration for plasma physics experiments.

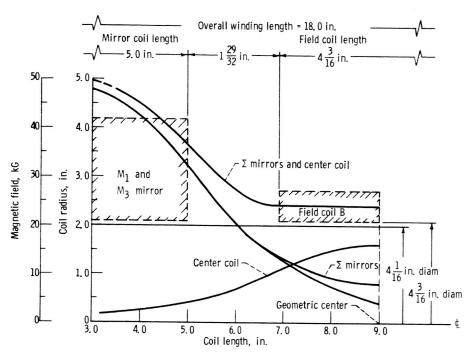
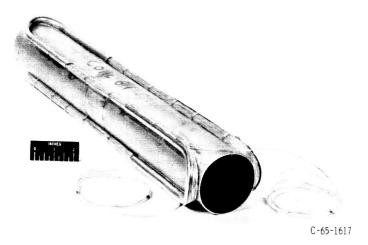
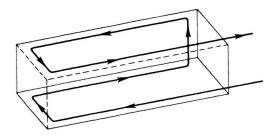


Fig. 10. Design parameters for magnetic coils. Assumed current, 25 A/strand or 175 A/7 strand cable; current density, 1.2×10^4 A/sq cm.



(a) Photograph showing coils.



(b) Schematic of current path in coil.

Fig. 11. - loffe bars (quadrupole configuration).

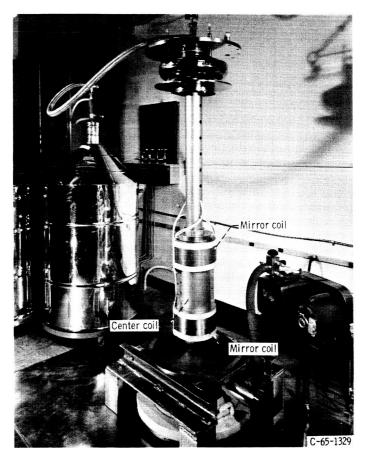


Figure 12. - Magnetic bottle.

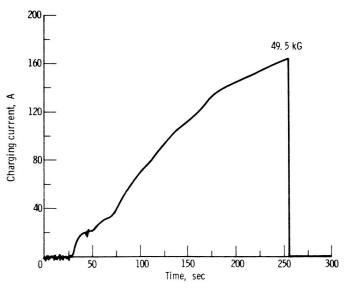


Fig. 13. Charging history, coil A alone.

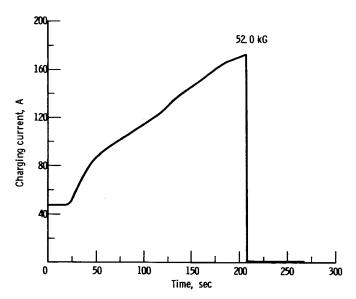


Fig. 14. Charging history, coil C alone.

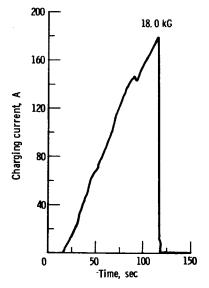


Fig. 15. Charging history, coil B alone.

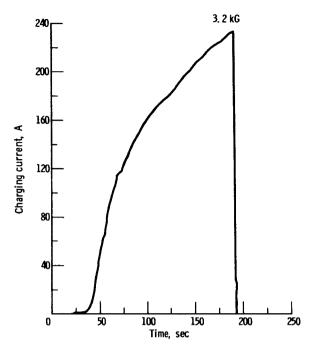


Fig. 16. Charging history, coil D alone.

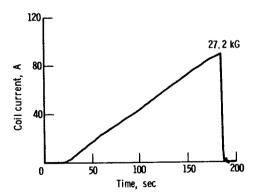


Fig. 17. Charging history, all four coils in series.

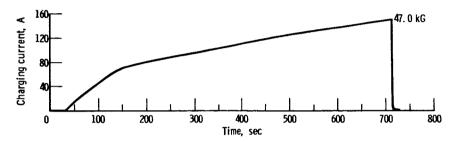


Fig. 18. Charging history, coils A, C, and B in series.